



Investigation into the viability of K-TIG for joining armour grade quenched and tempered steel

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ABSTRACT

Motivated by significant loss of mechanical properties during conventional fusion arc welding processes owing to under matching filler materials used and low efficiency associated with multipass welding, the viability of keyhole tungsten inert gas (K-TIG) welding for joining armour grade quenched and tempered (Q&T) steel was presented. Single pass full penetration was achieved on 9 mm thick plates at a speed of 28 cm/min⁻¹ without using any filler materials and edge preparation. In-depth investigation into the weld was conducted by optical microscope, scanning electron microscope, electron back-scattered diffraction, microhardness and tensile test. The results show that the weld metal consists of dendritic structure and predominantly bainitic microstructure and is dominated by low angle grain boundaries. Hardness distribution across the weld is higher than current practice, which would lead to improved ballistic performance. Although the joint efficiency of the weld is 65% due to reduction in weld metal hardness, it is still much higher than that produced via conventional fusion welding, which is not surpassing 50%. It has been demonstrated that the K-TIG welding process offers a new way to weld medium thick armour grade Q&T steel with high efficiency and low cost, while maintaining the mechanical properties at a high level.

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1. Introduction

Quenched and tempered (Q&T) steels are much harder and stronger than normal carbon steel and they possess high ratio of strength to weight which improves their structure efficiency. This unique property is obtained through a Q&T heat treatment and from its chemical composition. In addition, they possess a particular combination of high hardness, high strength with good weldability, toughness and ease of heat treatment, providing excellent resistance to shock and penetration. Therefore, they have been widely applied in situation where a combination of toughness, tensile strength, hardness as well as penetration resistance is required [1–4]. It is because the Q&T steels possess such unique property that they are mainly used for construction of hull and turret of military combat vehicles [5,6].

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Joining and welding of armour grade Q&T steels are certainly unavoidable in the fabrication process of armored vehicles. At current stage, welding techniques used to fabricate the weldment of this kind of steel are conventional fusion welding processes, such as Shielded Metal Arc Welding (SMAW), Flux Cored Arc Welding (FCAW) and Gas Tungsten Arc welding (GTAW) [7,8]. However, due to the under matching filler materials used, such as austenitic stainless steel (ASS) filler materials and low hydrogen ferritic (LHF) filler materials, mechanical properties of the weldment deteriorates dramatically compared with base metal, especially the hardness in the weld metal region [9–11]. It is known that the harder the materials, the better the ballistic performance [12]. In a bid to find ways to increase hardness in weld metal region, a hardfacing technique was introduced in which a hardfaced interlayer made of either chromium rich carbide or tungsten carbide is deposited between capping and root pass of ASS or LHF weld metal [13–17]. Although improved hardness and correspondingly ballistic performance was reported due to the very hard interlayer materials, the extremely inhomogeneous microstructure along the thickness direction in the weld metal region may not produce satisfactory mechanical properties, such as UTS and elongation. Furthermore, groove prepa-

ration, multipass welding, along with the use of large amount of expensive hardfaced interlayer filler materials make this technique less efficient and cost-effective.

In order to fabricate the joint of armour steel with low cost and high efficiency, the feasibility of hybrid Laser-Gas Metal Arc welding process for welding armour steel was studied by Kuzmikova et al. [18]. Besides improved hardness in weld metal region compared with conventional fusion welding process, it was also found that welding time and consumable usage can be reduced by 36% and 56% respectively due to the reduced deposition pass and fusion zone area. However, hybrid Laser-Gas Metal Arc welding process requires two welding equipment to operate at the same time, which intangibly increases the capital cost and complicates the control over welding parameters.

More recently, El-Batahy et al. [19] investigated the feasibility of friction stir welding (FSW) for welding 1640 MPa high strength Q&T steel. A defect free and full penetration weld with thickness of 2.2 mm was successfully achieved by FSW at a travel speed up to 600 mm/min⁻¹. In addition, the hardness in the weld metal region is similar or even higher than base metal when peak temperature experienced in weld metal region exceeds Ac₁ line. Nevertheless, the thickness of the high strength Q&T steel welded by FSW was merely 2.2 mm. Considering the critical durability and fatigue resistance of the FSW tool, FSW might not be suitable for welding armour grade Q&T steel with medium thickness. It is obvious that there is a need to find a process that is able to produce armour steel joint with high efficiency, low cost and superior mechanical properties, especially hardness.

Keyhole mode Tungsten Inert Gas Welding, also known as K-TIG, was invented by Commonwealth Scientific and Industrial Research Organisation (CSIRO). It is a process variant of the standard TIG welding, with the difference being that its functional mode leads to a keyhole shaped weld bath, just as the ones present in laser beam welding (LBW), electron beam welding (EBW) and plasma arc welding (PAW) process [20]. In K-TIG welding process, the cathode emission area is focused to a much smaller area compared with standard TIG, thus the current density and pinch effect is increased in the arc column. Once the welding current is increased to a high level, say more than 300 A, the arc pressure is sufficient to overcome the surface tension and hydrostatic head and it will displace the molten metal all the way through thickness to form a keyhole. Unlike EBW, LBW and PAW which rely on ablation pressure or stagnation pressure to create the keyhole, K-TIG uses a free-burning arc as the heat source and the pressure used to displace the metal aside is originated from the interaction between arc current and its self-induced magnetic field, which is completely electromagnetic in origin. Single pass full penetration weld with medium thickness (6–13 mm) can be readily achieved without using any filler materials and edge preparation at a speed of up to 1000 mm/min⁻¹, making it much more productive and efficient than conventional fusion welding. Furthermore, relatively simple torch configuration and high current capacity allows K-TIG welding process to be more simplified in the selection of welding parameters and much faster (3-folds) than PAW. K-TIG also has advantages over LBW and EBW in terms of equipment cost and being tolerant of joint preparation since the latter two tend to produce a slim weld seam, which leads to a poor gap bridging ability and requires high precision edge preparation and set-up [18,21].

The successful operation of keyhole mode TIG welding relies on many factors, including physical properties of materials and welding parameters. For the K-TIG weld to be completed the keyhole has to close behind the arc, and this places a fundamental constraint: the molten metal must be held in place by surface tension while it is solidifying [22,23]. This constraint in turn leads to a balance equation

in the rear weld pool between surface tension and hydrostatic head as shown below:

$$wh \leq \gamma / \rho g \quad (1)$$

Where γ is surface tension, w is the width of the root bead, ρ is the density of materials, g is acceleration due to gravity and h is the plate thickness. It is evident from Eq. (1) that the width of root bead will determine the maximum thickness that could be welded by K-TIG welding process. As the width of the root bead is going to increase with increasing thermal conductivity [24], the possibility of destabilizing the keyhole is increased with increasing thickness and/or thermal conductivity. It is largely for this reason that K-TIG welding process has been confined to materials with low thermal conductivity, such as stainless steel and titanium alloy [23].

Due to the nature of high productivity and low cost, joining of mid-thickness materials with low thermal conductivity by K-TIG welding has already been adopted and demonstrated in industry, such as CP titanium by Lathabai et al. [23], zirconium by Lathabai et al. [25], stainless steel by Lohse et al. [26] and Feng et al. [27]. Motivated by applying K-TIG to weld materials with relatively high thermal conductivity, such as carbon steel, Fang et al. [28] and Liu et al. [29] tried to use K-TIG to weld Q345 and 16Mn structural steel respectively in the form of bead-on-plate. Although favorable mechanical properties were achieved on both cases, the thickness of materials that subject to investigation was less than 6 mm (5.5 mm). Overall, it is obvious that K-TIG technology is relative mature in terms of welding materials with lower thermal conductivity. At current stage, welding of carbon steel via K-TIG process is confined to bead-on-plate welding and thin plates which are less than 6 mm thick. As mentioned above, the advantage of K-TIG is to weld medium thickness materials at high speed. Thus, in order to fulfill its maximum potential, the feasibility of K-TIG for joining carbon steels with medium thickness should be evaluated, especially for butt joint welding.

In this paper, K-TIG welding was conducted on 9 mm-thick armour grade Q&T steel in flat position. The effect of varying heat input on the surface morphology were analyzed, followed by the characterization of microstructure in both weld metal and heat-affected zone (HAZ) as well as mechanical properties of the weldment. The research results may pave ways for use of K-TIG to weld medium thick armour plates.

2. Experimental procedure

2.1. Materials

The armour grade Q&T steel subject to investigation in this paper conforms to the requirement of MIL-DTL-46100 and falls into the category of a family of Q&T steels for armour applications. This high hardness armour steel is manufactured by BluscopeSteel utilising the Basic oxygen steelmaking (BOP) process, including vacuum degassing and calcium treatment, followed by hot rolling to desired thickness and heat treatment involving quenching and low temperature tempering to achieve desired combination of hardness and toughness. Two plates, each with the dimension of 150 mm × 150 mm × 9 mm, were applied to prepare for the butt joint plates. The chemical composition of the investigated armour steel is listed in Table 1. The microstructure of the parental metal is present in Fig. 1 and is mainly composed of tempered martensite with typical lath shape.

2.2. Welding set-up

The welding machine used in this study is manufactured by Keyhole TIG Limited (an Australian company). It consists mainly of

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